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RESEARCH ARTICLE

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Effects of the Ebbinghaus figure on grasping are not only due to misjudged size

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Abstract It is not evident how the small effects of the flankers of the Ebbinghaus figure on peak grip aperture (PGA) should be interpreted. One interpretation is that the flankers influence the estimated size, which in turn influences the grasp. If this interpretation is correct, then only the size-dependent aspects of the grasping movement should depend on the spatial positions of the flankers. An alternative interpretation is that the effect on grip aperture is caused by a change in judgement of the required precision, in which case various aspects of the grasping movement could be influenced by the size and position of the flankers. We presented subjects with a display consisting of a central disk surrounded by four large or small flankers. The array of circular flankers could be rotated by 45°. There were two tasks: to reproduce the perceived size of the central disk, and to grasp the central disk. As in other studies, the reproduced size and the PGA were both influenced by the size of the flankers. The effect on reproduced size settings was independent of the flankers' spatial position. Nevertheless, the flankers' position did influence the final grip aperture and the grip orientation at PGA and at movement offset. Because the flankers changed more than only the PGA, we conclude that the effect of the flankers on prehension cannot only be because of misjudgement of the size of the central disk.

Keywords Prehension · Perception · Action · Illusion

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Introduction

The Ebbinghaus illusion is the phenomenon that a central circle surrounded by large circular flankers is perceived to be smaller than a similar central circle surrounded by small flankers. Aglioti et al. (1995) performed an experiment in which subjects had to judge which of two central target disks was larger (or smaller), and then they had to grasp that disk. The influence of the illusion on peak grip aperture (PGA) was smaller than on the perceptual settings. They concluded that despite the illusion the grasping movements remained accurate. A study by Haffenden and Goodale (1998) gave similar results: two sizes of flankers had significantly different effects on manual size estimation, but not on grasping. In both these studies, however, the illusion did have some effect on PGA (Table 1). What causes this effect of the flankers on grasping?

Franz et al. (2000) proposed that the same illusory size information is used in perception and in grip scaling. They showed that if the perceptual task is designed to more closely match the grasping task (i.e. to involve a single target) the effects on grasping and perception are not significantly different (Pavani et al. 1999; Franz et al. 2000, 2003). An overview of the experimental results (Table 1) seems to support the interpretation that the PGA and the perceptual measure are influenced to the same extent if a single target is used (Haffenden et al. 2001 is an exception). We will refer to this view as the "illusory size hypothesis".

Haffenden and Goodale (2000), (also see Haffenden et al. 2001) proposed that the small effect of the Ebbinghaus illusion on grip scaling does not result from misperceiving the size, but from a direct influence of the flankers on the movement path (obstacle avoidance). We will refer to this view as the "illusory precision hypothesis". Haffenden and Goodale (2000) predicted that if this view is correct two-dimensional rectangular flankers (potential obstacles) surrounding a target disk would affect grasping if they were adjacent to the contact

Table 1 Magnitude of the effect of the Ebbinghaus illusion on perceptual judgements and on the peak grip aperture (PGA)

Study	Number of targets[a]	Perception	PGA
Aglioti et al. (1995)	2	2.5 (0.2)	1.6 (0.4)
Haffenden and Goodale (1998)[f]	2	4.2 (1.0)[d]	1.0 (0.5)
Pavani et al. (1999)	1	0.7	1.0
Franz et al. (2000)	1	1.5 (0.1)	1.5 (0.4)
Haffenden et al. (2001)	1	2.6 (0.4)[b, d]	0.2 (0.3)
Hanisch et al. (2001)	2	1.5 (0.5)[e]	0.8 (0.6)[e]
Glover and Dixon (2002)	1	2.1 (0.4)[d]	1.4[c] (0.3)
Franz (2003)	1	1.6[c, d]/1.1[c]	1.8[c]
Franz et al. (2003)	1	1.4 (0.2)[n]	1.5 (0.3)[n]
		1.3 (0.1)[f]	1.2 (0.3)[f]
Kwok and Braddick (2003)	2	2.0[d]	1.0

All illusion effects are differences between values for small and large flankers expressed in mm (with standard errors when given)n/f denotes data for the conditions "near" and "far" respectively. Data provided by Franz

[a]Number of targets visible simultaneously

[b]Only the conditions "adjusted small" and "traditional large" are included

[c]Scaled illusion effect

[d]Manual size estimation (participants indicated target size by opening index finger and thumb) rather than comparison of two central circles or adjustment of an isolated circle

[e]Only the adult group is included

[f]The values from this study are obtained from Table 1 of Franz 2001

points of the digits, but not if they were at other positions. The predicted effect of the spatial position of the flankers on the PGA did not reach significance. Changing the distance between the target object and the flankers in the Ebbinghaus figure did influence PGA, but Franz et al. (2003) found similar effects of the distance between the target and the flankers on perception as on the PGA. Thus the empirical support for this view is quite limited.

Although we too have previously argued that perception and action use the same visual information (Smeets et al. 2002), we have also argued that visual estimates of size are not used in grasping (Smeets and Brenner 1999). If so, then the effect of the flankers on PGA cannot be due to a misjudgement of size. Could it be that the effects are at least partially due to changes in judgements of the required precision (Smeets et al. 2003)?

In order to try to distinguish between the above mentioned proposals, we performed an experiment with a version of the Ebbinghaus illusion that was designed to separate illusory size effects from illusory precision effects. We varied the positions of the flankers relative to the movement, an aspect that was expected to be irrelevant to the (mis)perceived size but that could influence judgements of the required precision (Fig. 1). To be able to vary the spatial position of the flankers (potential obstacles) by a substantial amount without changing their distance from the object, we used four circular flankers only. If the illusory effect of the Ebbinghaus

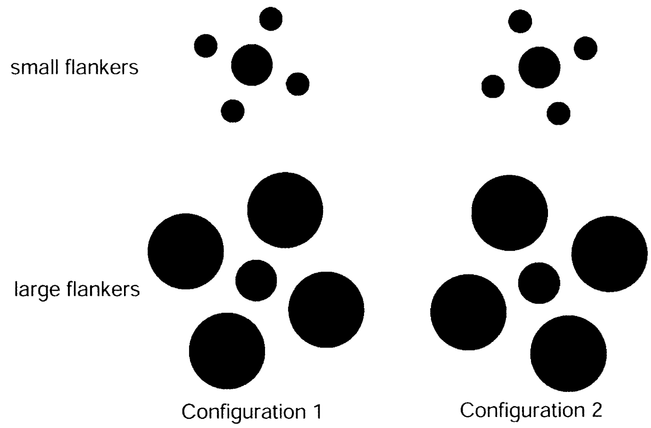


Fig. 1 The four combinations of flanker size and configuration used in the experiment. The only difference between the two configurations is that the flankers have been rotated by 45°

figure is caused by the flankers changing estimates of the required precision, aspects of grasping such as grip orientation are likely to depend on the spatial position of the flankers. If the illusory effect is caused by illusory size information, the PGA should only depend on the spatial position of the flankers if the perceived size does, and no other aspects of grasping should depend on the flankers' position. Because Franz et al. (2003) showed that perceptual judgement can change with the spatial position of the flankers, we first tested whether the spatial position of four circular flankers surrounding the target disk has an effect on perceptual size settings. After that, subjects were asked to grasp the target disks. We examined the movement time (MT), the peak velocity (PV), the time to peak velocity (TPV), the orientation of the grip at two instances, the PGA, the time to PGA and the final grip aperture (FGA).

Materials and methods

Subjects

This study is part of an ongoing research program that has been approved by the local ethics committee. Twelve right-handed colleagues volunteered to take part in the study after being informed about what they would be required to do.

Apparatus and stimulus

The stimulus consisted of a single black central circle surrounded by four black (large or small) circular flankers, all on a white background. The stimulus was projected from below on to a projection surface. The resolution of the projected image was 1,024×768 pixels, with 1 pixel corresponding to about 0.4 mm. The large and small flankers were 55 mm and 17 mm in diameter, respectively. The diameter of the central circle could be

28, 30, or 32 mm. The distance from the edge of the central target disk to the nearest edge of the flanker was 12.5 mm, irrespective of flanker size. For each flanker size there were two possible configurations of the Ebbinghaus figure. The only difference between them was that the spatial position of the flankers was changed—the array of flankers could be in two configurations differing by 45° in orientation (Fig. 1).

In the perceptual task, an isolated comparison circle was displayed after the stimulus. The position of the comparison circle was chosen at random within an area of about 16 mm laterally and 24 mm in the sagittal direction. The centre of this area was 15 cm to the right of the centre of the original stimulus. The size of the comparison circle was initially set to a random value between 10 mm and 50 mm.

In the grasping task a real black target disk was placed on top of the projected central target circle. Its diameter was exactly the same as that of the projected central target circle. To make the grasping task comparable with the perceptual task, the height of the target disk was only 3 mm, which was hardly noticeable for the near-orthogonal viewing. Due to the difference in material, however, subjects could clearly see this was a real object. Because of this difference in the material of the stimulus in the perceptual setting and the grasping stimuli, the magnitude of the illusion might differ slightly. We will, therefore, not directly compare the magnitude of the influence of the illusion on grasping with that on perception. The projected circular flankers were exactly the same as in the perceptual task. A black starting position (diameter 2 mm) was projected 30 cm to the right of the central circle. The set-up of the grasping task is shown in Fig. 2.

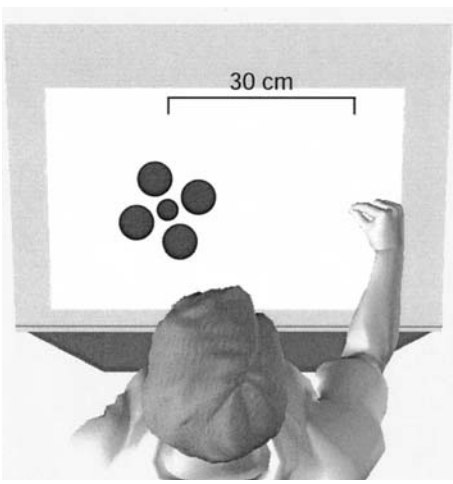


Fig. 2 Top view of the experimental set-up. Subjects have their thumb and index finger pinched together at the starting position (30 cm from the centre of the target disk) and their eyes closed. After a verbal signal subjects open their eyes and grasp the thin central target disk

Procedure

In each trial of the perceptual task a stimulus was presented for 1.5 s. Immediately after it disappeared, the isolated comparison circle was presented. The subject's task was to reproduce the central target circle by adjusting the size of the comparison circle. They did so by moving the mouse horizontally (changing the position of the mouse changed the size of the comparison circle). Subjects adjusted its size until it was perceived to be the same size as the former central target circle. When the subjects were satisfied with their setting they pressed the mouse button and after 1 s a new stimulus appeared. During the task subjects had unrestricted vision. There was no time limit for the reproduction. Each subject performed 120 trials (3 sizes of the target disk×2 sizes of flanker×2 configurations×10 repetitions) in a completely random order.

In the grasping task trajectories of finger movements were recorded using an Optotrak System (sampling rate 250 Hz, resolution 0.01 mm). Infra-red-emitting diodes (IREDs) were attached to the nail of the thumb and the index finger of the right hand. Before each trial the starting position was presented. Subjects pinched their thumb and index finger together at this starting position and closed their eyes. The stimulus was then presented and the experimenter put the target disk exactly on the projection of the central circle. The subject was instructed to open his/her eyes, grasp the target disk at a comfortable pace, and place the disk on the right side of the surface. The experimenter removed the target disk, and the starting position for the next trial was presented. Each subject performed the same 120 trials as in the perceptual task in a new random order.

Data analysis

Instantaneous velocity was computed from position samples of the IREDs. To do so we fit a second-order polynomial to seven position samples (24 ms window) centred at each position. Based on the parameters of the fit we estimated the finger's velocity at that instant. Movement onset is defined for each digit as the last frame before PV in which the tangential velocity was smaller than that on the preceding frame. Movement offset was defined as the first frame after PV in which the velocity component in the direction perpendicular to the surface changed sign (i.e. when the digit started moving upwards). The MT was defined as the time between the movement onset of the digit that started moving first and the movement offset of the digit that stopped last. This procedure ensured we included the whole movement. To characterize the velocity profile we determined the relative time to peak velocity (TPV), which is the fraction of the MT at which the PV occurred.

Peak grip aperture was defined as the maximum distance between the thumb and the index finger IREDs.

Smeets et al. (2003) predict that if a larger PGA is due to changed accuracy constraints, it should occur earlier. We therefore determined the relative time to PGA (TPGA) as the fraction of the MT at which the PGA occurred. Final grip aperture (FGA) is the distance between the thumb and the index finger IRED at movement offset. Grip orientation was defined as the orientation of the projection on to the plane of the Ebbinghaus figure of a straight line connecting the positions of the IREDs on the finger and thumb (0° is to the right). This angle was determined both at PGA and at movement offset.

A scaled illusion effect was calculated for the reproduced size and for the PGA (in accordance with Franz et al. 2001). For each subject the effect of the size of the flankers was divided by the slope relating the measures in question to the physical size, so that the influence of the illusion could be expressed as an equivalent change in actual size.

An important prediction of the illusory size hypothesis is that for subjects who are perceptually very susceptible to the illusion the flankers should also have a large effect on PGA. Such correlations have been used to show that perception and action are based on the same visual information (Lopez-Moliner et al. 2003). To test this we calculated the correlation between the magnitudes of the effect of the illusion on the perceptual judgements and on the PGA across subjects.

Statistical tests were all conducted across subjects. In both tasks data were analysed with repeated-measures ANOVA with the factors target size (three levels: 28, 30, 32 mm), size of the flankers (two levels: large, small) and spatial position of the flankers (two levels: configurations 1 and 2). Values are presented as means ± standard errors between subjects. A significance level of $\alpha = 0.05$ was used for all statistical analyses. In the perceptual task the dependent variable was the reproduced size of the comparison circle. In the grasping task the dependent variables were: PGA, FGA, grip orientation at PGA and at movement offset, MT, PV, relative time to peak grip aperture (TPGA), and relative TPV.

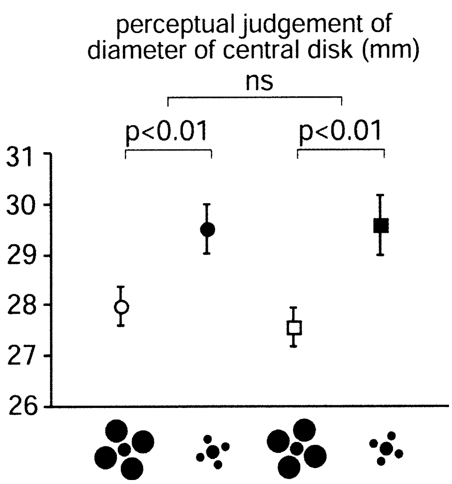


Fig. 3 Results from the perceptual judgement task averaged over the three target sizes. *Error bars* represent standard errors between subjects

Results

In the perceptual task the reproduced size of the comparison circle was influenced both by the real target size (slope: 0.67 ± 0.11) and by the size of the flankers (Fig. 3). The unscaled illusion effect (difference between a target surrounded by small flankers and one by large flankers) was 1.8 ± 0.3 mm. The scaled illusion effect shows that surrounding a target disk by large flankers rather than by small flankers has the same influence as making it 2.7 mm smaller ($P < 0.01$). No difference was found between the reproduced size of the two spatial positions of the flankers (configuration 1 vs configuration 2) and there were no significant interactions.

Figure 4 shows overall mean traces of the finger and thumb (averaged by the proportion of MT) for each configuration in the grasping task. As expected, subjects opened their hand wider than the size of the object. Grip orientation at the moment of PGA was influenced by the spatial position of the flankers (Fig. 5A, $P = 0.01$), as predicted by the illusory precision hypothesis. In configuration 1 the mean grip orientation was 75.4 ± 1.2°, and in configuration 2 it was 76.4 ± 1.2°. No interactions or other main effects were found. The grip orientation at movement offset was also influenced by the spatial position of the flankers (Fig. 5B, $P < 0.01$). In configuration 1 final grip orientation was 73.9 ± 1.3°, and in configuration 2 it was 75.1 ± 1.3°. No interactions or other main effects were found. The difference in grip orientation corresponds to a shift in the relative positions of finger and thumb of approximately 0.5 mm.

Neither the size or spatial position of the flankers nor the target size influenced the MT, and there were no significant interactions. The average MT was 820 ± 5 ms. There was a significant effect of target size on PV ($P < 0.05$). Movements to the smallest target (28 mm) had a larger PV (1.07 ± 0.02 m/s) than those to the other two (1.05 ± 0.02 m/s for both the 30 mm and 32 mm targets). No other main or interaction effects were found. Only a flanker size by spatial position interaction was found for the relative TPV ($P < 0.05$). On average, the PV occurred at 37.8 ± 0.3% of the movement.

The PGA scaled with target size and was influenced by the flanker size (Fig. 5c). An increase of actual target size by 2 mm led to an increase of the PGA of 1.96 mm, giving a slope of 0.98 ± 0.11. This slope is within the range of slopes found in other studies (for an overview see Smeets and Brenner 1999). The PGA was 1.0 mm smaller (± 0.2 mm) when the central target disk was surrounded by large flankers than when it was surrounded by small flankers. An interaction was found between target size and the spatial position of

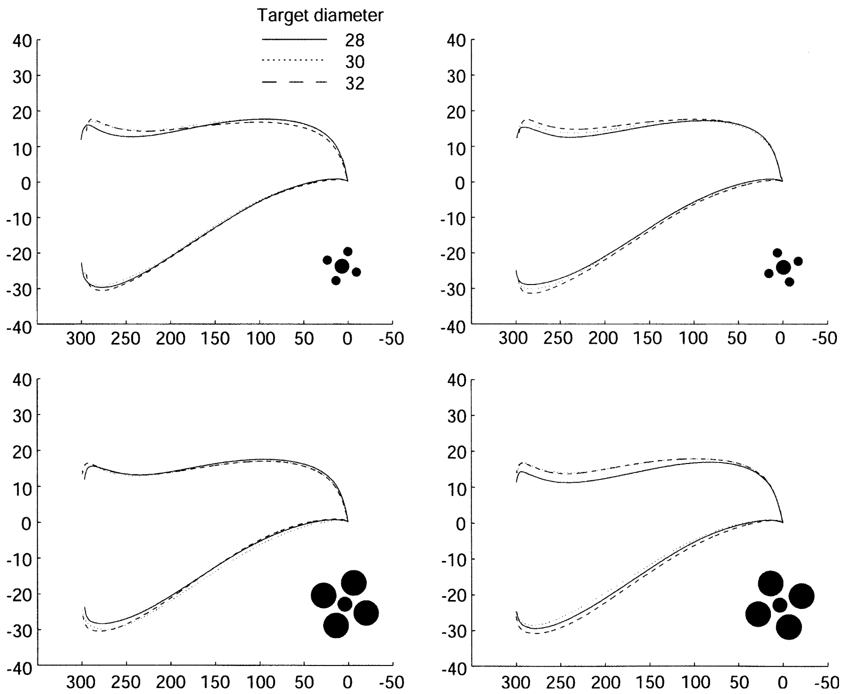


Fig. 4 Traces for finger and thumb, from the starting position on the right to the target object, averaged over subjects

the flankers ($P < 0.05$). For the flankers in configuration 1 the PGA scaled with target size with a slope of 1.22 ± 0.62. In configuration 2 the slope was 0.73 ± 0.61. No further significant effects were found. On average the PGA occurred at $68.0 \pm 0.8\%$ of the movement. No significant effects were found on the relative TPGA. Smeets et al. (2003) modelled the direct influence of the flankers as a change in precision; and predict that the PGA should be 0.06% earlier if it is 1 mm larger. We found no significant effect, but the data did not differ significantly from the model predictions either.

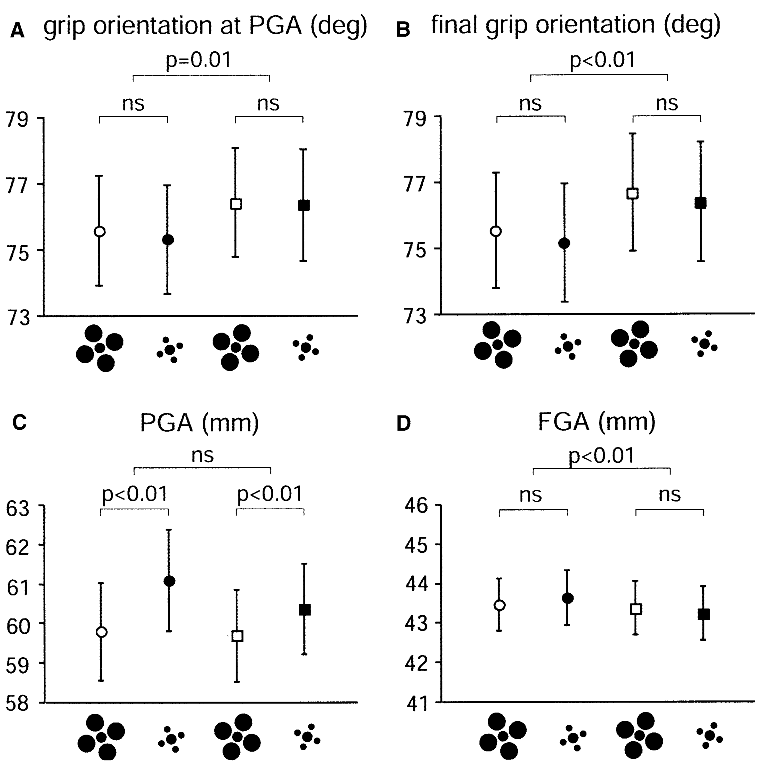


Fig. 5 Results for the grasping task averaged over the three target sizes. **A** Grip orientation at PGA. **B** Final grip orientation. **C** Peak grip aperture. **D** Final grip aperture. *Error bars* represent standard errors between subjects

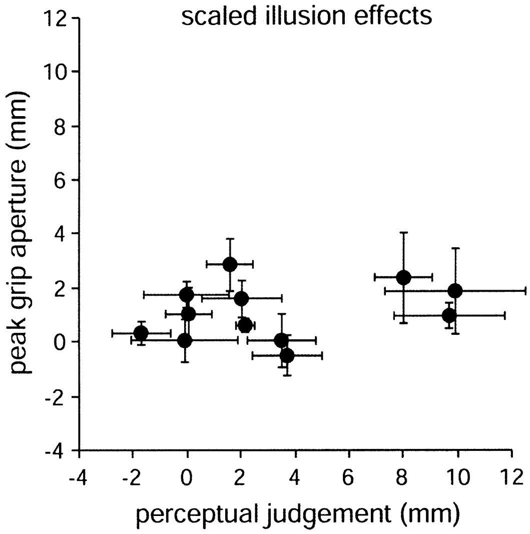


Fig. 6 Effects of flanker size on PGA as a function of their effect on reproduced size. Each symbol represents the effects averaged over target size and configuration for one subject. *Error bars* are standard errors across target sizes and flanker configurations

The FGA scaled with target size and was influenced by the spatial position of the flankers (Fig. 5D, $P < 0.01$). A physical increase in target size of 2 mm led to an increase of the FGA of 1.96 mm (slope 0.98 ± 0.03). In configuration 1 the average FGA was 43.6 ± 0.4 mm and in configuration 2 it was 43.3 ± 0.4 mm. An interaction was found between the size and the spatial position of the flankers ($P < 0.05$). In configuration 1 the FGA for the small flankers was 43.6 ± 0.7 mm and for the large flankers it was 43.5 ± 0.7 mm. In configuration 2 the FGA was 43.2 ± 0.7 mm and 43.4 ± 0.7 mm for the small and large flankers, respectively.

The influence of flanker size on perceptual settings differed substantially between subjects. As already mentioned, we are hesitant to directly compare the magnitude of the flankers' effects on the reproduced size with those on the PGA. However, if the grip apertures were related to these perceptual settings (as the illusory size hypothesis predicts) we would have expected to find a correlation between reproduced size and the PGA (Fig. 6). The PGA is not correlated with the scaled perceptual data ($R = 0.19$, $P = 0.57$).

Discussion

The difference between the perceptual judgements for a disk surrounded by large and small flankers in this study is equivalent to a change in size of 2.7 mm. Thus four flankers are enough to obtain the Ebbinghaus illusion. Moreover, changing the spatial position of the flankers without changing their distances from the target does not change their perceptual influence in the way that changing the distance between the flankers and the target does (Franz et al. 2003).

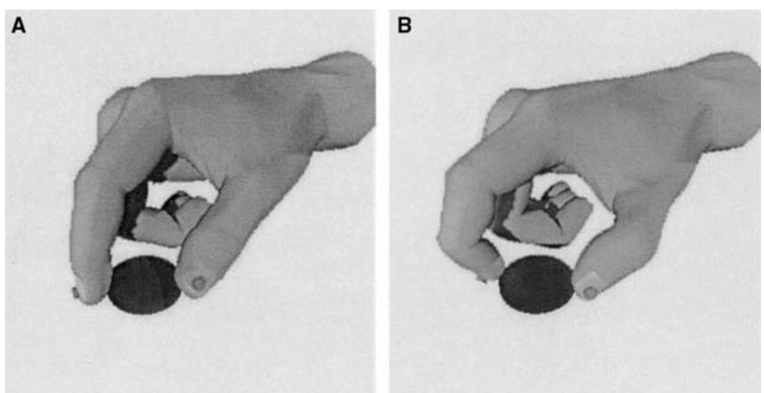
The grip orientation at PGA and at movement offset were both influenced by the spatial position of the flankers. Thus the flankers change the position at which the disk is grasped, which favours the illusory precision hypothesis. The spatial position of the flankers also changed the slope of the relationship between PGA and object size. Again, this is in line with the flankers directly interfering with the movements of the digits.

The PGA was influenced by the size of the flankers (1 mm difference between a target disk surrounded by large flankers and one surrounded by small flankers). The magnitude of this effect is within the range of effects that have previously been found in studies using the classical Ebbinghaus configuration (Table 1).

The effect of flanker orientation on the FGA means that subjects must have picked up the target object with a different grip force or orientation of the digits. For example, subjects could pick up the target object with the nails more perpendicular to the surface or with the nails more parallel to the object's surface (Fig. 7). The FGA, defined as the absolute distance between the IREDs, will differ when grasping in the manners shown in Figs. 7A and 7B, without changing the actual distance between the contact points of the digits.

Exactly how the subjects actually did pick up the targets cannot be determined using one IRED on each digit. In the studies of Franz et al. (2000, 2001) grip

Fig. 7 Picking up a target with the fingernails parallel to the surface (**A**) can produce a different marker distance than picking it up with the fingers perpendicular to the surface (**B**)



aperture was measured with three IREDs on each digit. With this method, digit orientation can be calculated and even the location of a point on the skin of the digits. However, the measured grip size will still depend on how the object is grasped, because the object will not always be grasped with the part of the digit for which the location is determined. Thus, although the effects of the flankers on grip orientation and FGA make us less confident about our measure of PGA, this does not change the fact that the flankers influence the grasp in a manner that is unrelated to perceived size.

Our study shows that conclusions should not be drawn on the basis of PGA alone. In previous studies conclusions about whether or not actions are susceptible to illusions as perception, were drawn on the basis of comparison of the effects of illusions on measures of the perceived size and on the PGA (Haffenden and Goodale 1998; Kwok and Braddick 2003; Aglioti et al. 1995). We show here that the Ebbinghaus figure can also influence grasping parameters that are not related to size perception. Since the grip aperture is not necessarily independent of such influences, the magnitude of the illusory effects on perception and PGA need not be identical; even if misjudging the central disk's size does influence our actions. Thus although the current results do not prove that the influence of the Ebbinghaus figure on grasping is independent of its effect on perceived size, they do show that the figure's influence cannot be fully explained by its influence on the perceived size. Hence, in any comparison, other effects of the illusion than its effect on perceived size must also be considered. This makes it very difficult to draw any definitive conclusions from such comparisons.

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